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for Operation-Based Conicts
in Model Versioning
Using Graph Modications**

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A Formal Resolution Strategy for Operation-Based Conflicts in Model Versioning Using Graph Modifications

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Abstract. In model-driven engineering, models are primary artifacts and can evolve heavily during their life cycle. Hence, versioning of models is a key technique which has to be offered by an integrated development environment for model-driven engineering. In contrast to text-based versioning systems, our approach takes abstract syntax structures in model states and operational features into account. Considering the abstract syntax of models as graphs, we define a model revision by a span $G \leftarrow D \rightarrow H$, called graph modification, where G and H are the old and new versions, respectively, and D the common subgraph that remains unchanged. Based on notions of behavioural equivalence and parallel independence of graph modifications, we are able to show a Local-Church-Rosser Theorem for graph modifications. The main goal of the paper is to handle conflicts of graph modifications which may occur in the case of parallel dependent graph modifications. The main result is a general merge construction for graph modifications that resolves all conflicts simultaneously in the sense that for delete-insert conflicts insertion has priority over deletion.

1 Introduction

Visual models are primary artifacts in model-driven engineering. Like source code, models may heavily evolve during their life cycle and should put under version control to allow for concurrent modifications of one and the same model by multiple

modelers at the same time. When concurrent modifications are allowed, contradicting and inconsistent changes might occur leading to versioning conflicts. Traditional version control systems for code usually work on file-level and perform conflict detection by line-oriented text comparison. When applied to the textual serialization of visual models, the result is unsatisfactory because the information stemming from abstract syntax structures might be destroyed and associated syntactic and semantic information might get lost.

Since the abstract syntax of visual models can be well described by graphs, we consider graph modifications to reason about model evolution. Graph modifications formalize the differences of two graphs before and after a change as a span of injective graph morphisms $G \leftarrow D \rightarrow H$ where D is the unchanged part, and we assume wlog. that $D \rightarrow G$ and $D \rightarrow H$ are inclusions. An approach to conflict detection based on graph modifications is described in [11]. We distinguish *operation-based* conflicts where deletion actions are in conflict with insertion actions and *state-based* conflicts where the tentative merge result of two graph modifications is not well-formed wrt. a set of language-specific constraints.

In this paper, we enhance the concepts of [11] by the resolution of operation-based conflicts of graph modifications. First of all, we define behavioural equivalence and parallel independence of graph modifications based on pushout constructions in analogy to algebraic graph transformations [4] and show a Local Church-Rosser Theorem for parallel independent graph modifications. Then we present a merge construction for conflict-free graph modifications and show that the merged graph modification is behavioural equivalent to the parallel composition of the given graph modifications. Using the minimal rule construction of [2,11], we are able to show that two graph modifications are parallel independent if and only if the graph transformations based on the minimal rules are parallel independent in the sense of the DPO-approach [4].

The main new idea of this paper is a general merge construction for graph modifications which coincides with the conflict-free merge construction if the graph modifications are parallel independent. Two graph modifications $m_1 = G \leftarrow D_1 \rightarrow H_1$ and $m_2 = G \leftarrow D_2 \rightarrow H_2$ are said to be in conflict if they are not parallel independent. A characterization result shows that (m_1, m_2) are in conflict if and only if (m_1, m_2) are in delete-delete conflict or (m_1, m_2) (resp. (m_2, m_1)) are in delete-insert conflict. Our general merge construction can be applied to conflicting graph modifications in particular. We establish a precise relationship between the behaviour of the given modifications and the merged modification concerning deletion, preservation and creation of edges and nodes. In our main result, we show in which way different conflicts of the given graph modifications are resolved by the merge construction which

gives insertion priority over deletion in case of delete-insert conflicts. Note, however, that in general the merge construction has to be processed further by hand, if other choices of conflict resolution are preferred for specific cases. Our running example is a model versioning scenario for statecharts where all conflicts are resolved by the general merge construction.

Structure of the paper: In Section 2, we present the basic concepts of algebraic graph modifications, including behavioural equivalence and a Local Church-Rosser Theorem. A general merge construction is presented and analysed in Section 4, where also the main result concerning conflict resolution is given³. Related work is discussed in Section 5, and a conclusion including directions for future work is given in Section 6.

2 Graph Modifications: Independence and Behavioural Equivalence

Graph modifications formalize the differences of two graphs before and after a change as a span of injective graph morphisms $G \leftarrow D \rightarrow H$ where D is the unchanged part. This formalization suits well to model differencing where identities of model elements are preserved for each element preserved. We recall the definition of graph modifications from [11] here:

Definition 1 (Graph modification). *Given two graphs G and H , a graph modification $G \xRightarrow{D} H$ is a span of injective morphisms $G \xleftarrow{g} D \xrightarrow{h} H$. A sequence $G = G_0 \Rightarrow G_1 \Rightarrow \dots \Rightarrow G_n = H$ of graph modifications is called graph modification sequence and is denoted by $G \xRightarrow{*} H$.*

Graph D characterizes an *intermediate graph* where all deletion actions have been performed but nothing has been added yet. Wlog. we can assume that g and h are inclusions, i.e. that D is a subgraph of G and of H . G is called *original graph* and H is called *changed* or *result graph*.

Example 1 (Graph modifications). Consider the following model versioning scenario for statecharts. The abstract syntax of the statechart in Figure 1 (a) is defined by the typed, attributed graph in Figure 1 (b). The node type is given in the top compartment of a node. The name of each node of type **State** is written in the attribute compartment below the type name. We model hierarchical statecharts by using containment edges. For instance, in Figure 1 (b), there are containment edges from

³ This technical report is an extended version of our contribution to FASE 2010 [5], containing full proofs.

superstate **S0** to its substates **S1** and **S2**⁴. Note that for simplicity of the presentation we abstract from transition events, guards and actions, as well as from other statechart features, but our technique can also be applied to general statecharts. Furthermore, from now on we use a compact notation of the abstract syntax of statecharts, where we draw states as nodes (rounded rectangles with their names as node ids) and transitions as directed arcs between state nodes. The compact notation of the statechart in Figure 1 (a) is shown in Figure 1 (c).

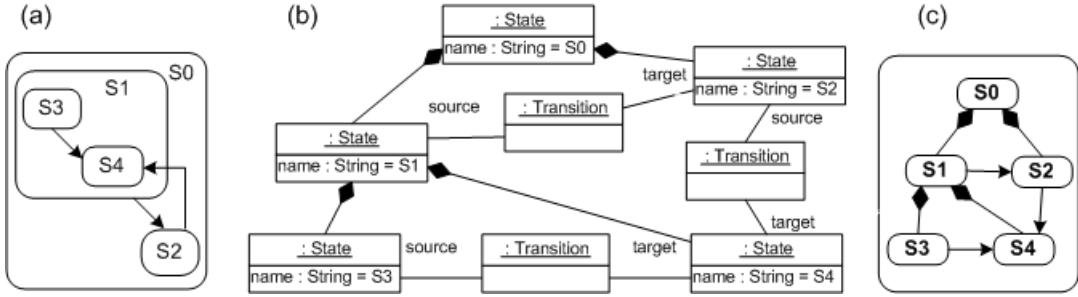


Fig. 1. Sample statechart: concrete syntax (a), abstract syntax graph (b), and compact notation (c)

In our model versioning scenario, two users check out the statechart shown in Figure 1 and change it in two different ways. User 1 performs a refactoring operation on it. She moves state **S3** up in the state hierarchy (cf. Figure 2). User 2 deletes state **S3** together with its adjacent transition to state **S4**.

Obviously, conflicts occur when these users try to check in their changes: state **S3** is deleted by user 2 but is moved to another container by user 1.

In this section, we study relations between different graph modifications based on category theory. In particular, we are interested in the parallel and sequential independence and behavioural equivalence of graph modifications leading to a Local Church-Rosser Theorem and a Merge Theorem. For this purpose, we need pullbacks, coproducts and pushouts of graphs as basic categorical constructions, corresponding to intersection, disjoint union resp. union of graphs in a generalized form. Due to this general formal setting, we can use different kinds of graphs like labelled, typed or typed attributed graphs (see [4] for more details). At first, we consider the sequential and parallel composition of two graph modifications. Our intention is that

⁴ In contrast to UML state machines, we distinguish edges that present containment links by composition decorators.

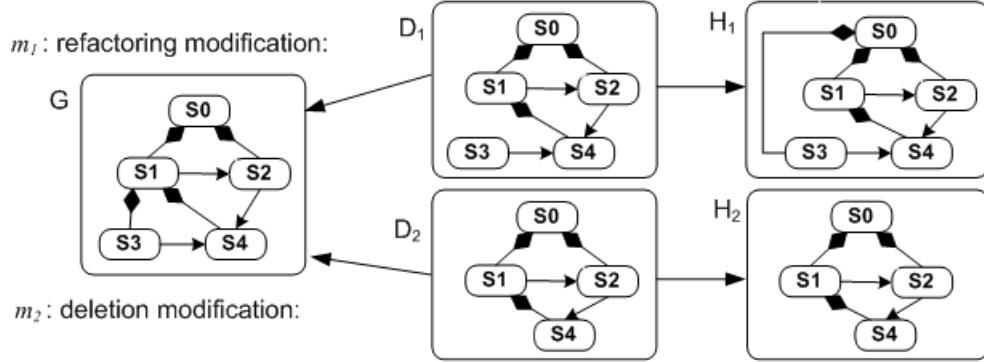


Fig. 2. Graph modifications m_1 (refactoring) and m_2 (deletion)

graph modifications are closed under composition. Given the sequential composition of two graph modifications $G \xRightarrow{D_1} H_1$ and $H_1 \xRightarrow{D_2} H_2$, the resulting modification obviously has G as original and H_2 as changed graph. But how does their intermediate graph D should look like? The idea is to construct D as intersection graph of D_1 and D_2 embedded in H_1 . This is exactly realized by a pullback construction. The parallel composition of two graph modifications means to perform both of them independently of each other by componentwise disjoint union. This corresponds to coproduct constructions $G_1 + G_2, D_1 + D_2$ and $H_1 + H_2$ on original, intermediate and changed graphs.

Definition 2 (Composition of graph modifications). *Given two graph modifications $G \xRightarrow{D_1} H_1 = (G \leftarrow D_1 \rightarrow H_1)$ and $H_1 \xRightarrow{D_2} H_2 = (H_1 \leftarrow D_2 \rightarrow H_2)$, the sequential composition of $G \xRightarrow{D_1} H_1$ and $H_1 \xRightarrow{D_2} H_2$, written $(G \leftarrow D_1 \rightarrow H_1) * (H_1 \leftarrow D_2 \rightarrow H_2)$ is given by $G \xRightarrow{D} H_2 = (G \leftarrow D \rightarrow H_2)$ via the pullback construction*

$$\begin{array}{ccccc} G & \leftarrow & D_1 & \longrightarrow & H_1 & \leftarrow & D_2 & \longrightarrow & H_2 \\ & & & \searrow & & \swarrow & & & \\ & & & D & & & & & \end{array}$$

(PB)

The parallel composition of $G_1 \xRightarrow{D_1} H_1$ and $G_2 \xRightarrow{D_2} H_2$ is given by coproduct construction: $G_1 + G_2 \xRightarrow{D_1 + D_2} H_1 + H_2 = (G_1 + G_2 \leftarrow D_1 + D_2 \rightarrow H_1 + H_2)$.

The differences between the original and the intermediate graph as well as between the intermediate and the changed graph define the behaviour of a graph modification. The same behaviour can be observed in graphs with more or less context. Therefore, we define the behavioural equivalence of two graph modifications as

follows: Starting with two modifications $m_i = (G_i \xRightarrow{D_i} H_i)$ ($i = 1, 2$), we look for a third graph modification $G \xRightarrow{D} H$ modeling the same changes with so little context that it can be embedded in m_1 and m_2 . A behaviourally equivalent embedding of graph modifications can be characterized best by two pushouts as shown in Definition 3, since the construction of a pushout ensures that G_i are exactly the union graphs of G and D_i overlapping in D . Analogously, H_i are exactly the union graphs of H and D_i overlapping in D ⁵

Definition 3 (Behavioural Equivalence of Graph Modifications).

Two graph modifications $G_i \xRightarrow{D_i} H_i$ ($i = 1, 2$) are called behaviourally equivalent if there is a span $(G \leftarrow D \rightarrow H)$ and PO-span morphisms from $(G \leftarrow D \rightarrow H)$ to $(G_i \leftarrow D_i \rightarrow H_i)$, ($i = 1, 2$), i.e. we get four pushouts in the diagram to the right.

$$\begin{array}{ccccc} G_1 & \longleftarrow & D_1 & \longrightarrow & H_1 \\ \uparrow & (PO) & \uparrow & (PO) & \uparrow \\ G & \longleftarrow & D & \longrightarrow & H \\ \downarrow & (PO) & \downarrow & (PO) & \downarrow \\ G_2 & \longleftarrow & D_2 & \longrightarrow & H_2 \end{array}$$

Remark 1. Behavioural equivalence of graph modifications is a congruence. This means, it is reflexive, symmetric and transitive and compatible with sequential and parallel composition.

Example 2. Figure 3 shows two behaviourally equivalent graph modifications where the upper one is the refactoring modification m_1 from Figure 2. The span $(G \leftarrow D \rightarrow H)$ shows the same changes as in m_1 and m_2 , but in less context.

We want to consider graph modifications to be parallel independent if they do not interfere with each other, i.e. one modification does not delete a graph element the other one needs to perform its changes. While nodes can always be added to a graph independent of its form, this is not true for edges. An edge can only be added if it has a source and a target node. Thus parallel independence means more concretely that one modification does not delete a node that is supposed to be the source or target node of an edge to be added by the other modification. Moreover, both graph modifications could delete the same graph elements. It is debatable whether the common deletion of elements can still be considered as parallel independent or not. Since we consider parallel independent modifications to be performable in any order, common deletions are not allowed. Once modification m_1 has deleted a graph element, it cannot be deleted again by modification m_2 ⁶

⁵ In the framework of algebraic graph transformations [4], we may also consider graph modification $G \xRightarrow{D} H$ as a graph rule r which is applied to two different graphs G_1 and G_2 . Since the same rule is applied, graph transformations $G_i \xRightarrow{r} H_i$ ($i = 1, 2$) would be behaviourally equivalent.

⁶ However, we will see that modifications with common deletions still can be merged.

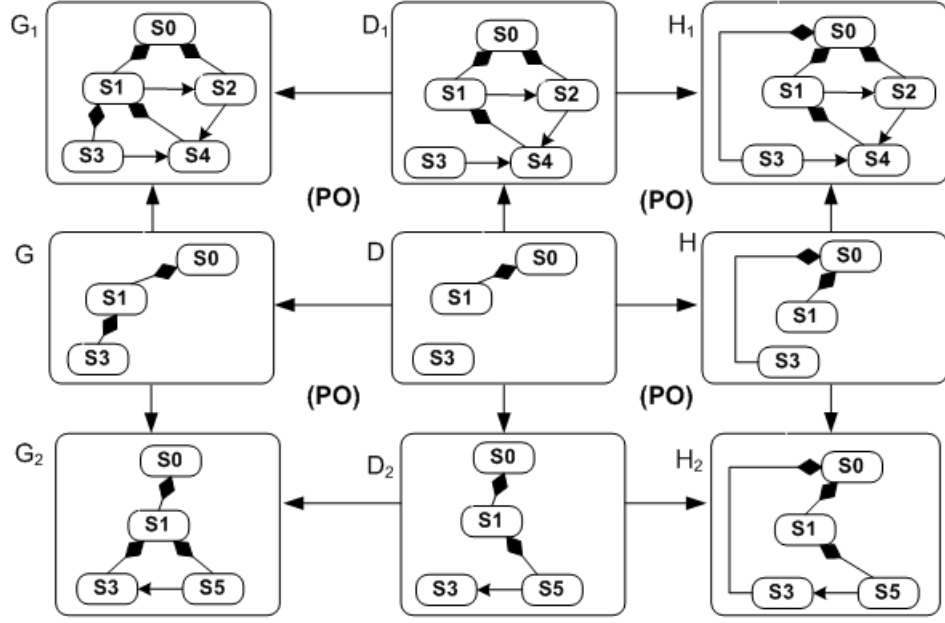


Fig. 3. Graph modifications m_1 and m_2 are behaviourally equivalent

This kind of parallel independence is characterized by Definition 4 as follows: At first, we compute the intersection D of D_1 and D_2 in G by constructing a pullback. Since common deletions are not allowed, there has to be at least one modification for each graph element which preserves it. Thus, D_1 glued with D_2 via D has to lead to G , which corresponds to pushout (1). Next, considering D included in D_1 included in H_1 we look for some kind of graph difference. We want to identify those graph elements of H_1 that are not already in D_1 and have to be added by D_3 such that both overlap in D , i.e. H_1 becomes the pushout object of $D \rightarrow D_1$ and $D \rightarrow D_3$. In this case, D_3 with $D \rightarrow D_3 \rightarrow H_1$ is called pushout complement of $D \rightarrow D_1 \rightarrow H_1$ (see [4] for pushout and pushout complement constructions). Analogously, D_4 is the difference of H_2 and D_2 modulo D . Finally, both differences D_3 and D_4 are glued via D resulting in H . According to Proposition 1, both modifications may occur in any order, such that Definition 4 reflects precisely our intention of parallel independence.

Definition 4 (Parallel Independence of Graph Modifications).

Two graph modifications $(G \leftarrow D_i \rightarrow H_i)$, $(i = 1, 2)$ are called parallel independent if we have the four pushouts in the diagram to the right, where (1) can be constructed as pullback, (2) and (3) as pushout-complements and (4) as pushout.

$$\begin{array}{ccccc} G & \longleftarrow & D_1 & \longrightarrow & H_1 \\ \uparrow & (1) & \uparrow & (2) & \uparrow \\ D_2 & \longleftarrow & D & \longrightarrow & D_3 \\ \downarrow & (3) & \downarrow & (4) & \downarrow \\ H_2 & \longleftarrow & D_4 & \longrightarrow & H \end{array}$$

Remark 2.

1. Parallel independence requires that pullback (1) is a pushout, i.e. $D_1 \rightarrow G \leftarrow D_2$ are jointly surjective, and that the pushout-complements D_3 in (2) and D_4 in (3) exist. Since all morphisms are injective, we only have to check that the dangling points of $D_1 \rightarrow H_1$ and $D_2 \rightarrow H_2$ are in D .
2. $(G \leftarrow D_1 \rightarrow H_1)$ and $(G \leftarrow D_2 \rightarrow H_2)$ are called *almost parallel independent* if (1) is pullback and (2) – (4) are pushouts.

Definition 5 (Sequential Independence of Graph Modifications). Two graph modifications $G \leftarrow D_1 \rightarrow H_1$ and $H_1 \leftarrow D_3 \rightarrow H$ are called sequentially independent if $H_1 \leftarrow D_1 \rightarrow G$ and $H_1 \leftarrow D_3 \rightarrow H$ are parallel independent.

Remark 3. Sequential independence requires by definition the four pushouts on the left which are equivalent to the four pushouts on the right where given $G \leftarrow D_1 \rightarrow H_1$ and $H_1 \leftarrow D_3 \rightarrow H$, (2) is constructed as pullback, (1) and (4) are constructed as pushout-complements, and (3) as pushout:

$$\begin{array}{ccccc} H_1 & \longleftarrow & D_1 & \longrightarrow & G \\ \uparrow & (1) & \uparrow & (2) & \uparrow \\ D_3 & \longleftarrow & D & \longrightarrow & D_2 \\ \downarrow & (3) & \downarrow & (4) & \downarrow \\ H & \longleftarrow & D_4 & \longrightarrow & H_2 \end{array} \quad \begin{array}{ccccc} G & \longleftarrow & D_1 & \longrightarrow & H_1 \\ \uparrow & (1) & \uparrow & (2) & \uparrow \\ D_2 & \longleftarrow & D & \longrightarrow & D_3 \\ \downarrow & (3) & \downarrow & (4) & \downarrow \\ H_2 & \longleftarrow & D_4 & \longrightarrow & H \end{array}$$

Proposition 1 (Local Church-Rosser for Graph Modifications).

1. Given parallel independent graph modifications $G \xRightarrow{D_i} H_i (i = 1, 2)$. Then, there exists H and graph modifications $H_1 \xRightarrow{D_3} H$, $H_2 \xRightarrow{D_4} H$ which are behaviourally equivalent to $G \xRightarrow{D_2} H_2$, $G \xRightarrow{D_1} H_1$, respectively, and $G \xRightarrow{D_1} H_1 \xRightarrow{D_3} H$, $G \xRightarrow{D_2} H_2 \xRightarrow{D_4} H$ are sequentially independent and the sequential compositions are equal.

$$\begin{array}{ccc} G & \xRightarrow{D_1} & H_1 \\ D_2 \Downarrow & & \Downarrow D_3 \\ H_2 & \xRightarrow{D_4} & H \end{array}$$

2. Given sequential independent graph modifications $G \xRightarrow{D_1} H_1 \xRightarrow{D_3} H$. Then, there exists H_2 and graph modifications $G \xRightarrow{D_2} H_2 \xRightarrow{D_4} H$ which are behavioral equivalent to $H_1 \xRightarrow{D_3} H$, $G \xRightarrow{D_1} H_1$, respectively, such that $G \xRightarrow{D_2} H_2 \xRightarrow{D_4} H$ are sequentially independent and $G \xRightarrow{D_1} H_1$, $G \xRightarrow{D_2} H_2$ are parallel independent and the sequential compositions are equal.

$$\begin{array}{ccc}
 G & \xRightarrow{D_1} & H_1 \\
 \Downarrow D_2 & & \Downarrow D_3 \\
 H_2 & \xRightarrow{D_4} & H
 \end{array}
 \qquad
 \begin{array}{ccccc}
 G & \xleftarrow{D_1} & & \xrightarrow{D_1} & H_1 \\
 \uparrow (1) & & \uparrow & & \uparrow (2) \\
 D_2 & \xleftarrow{D} & D & \xrightarrow{D} & D_3 \\
 \downarrow (3) & & \downarrow & & \downarrow (4) \\
 H_2 & \xleftarrow{D_4} & & \xrightarrow{D_4} & H
 \end{array}$$

Proof.

1. Given parallel independent graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$), we have pushouts (1) – (4) by Definition 4 leading to $H_1 \xRightarrow{D_3} H$ and $H_2 \xRightarrow{D_4} H$ with behavioural equivalence according to Definition 3. According to Definition 5 we have the required sequential independence. The sequential compositions are equal because (2) and (3) are also pullbacks and (1) and (2) commute.
2. By dualization of 1. □

Remark 4. The Local Church-Rosser Theorem for graph modifications can be extended analogously to the Local Church-Rosser Theorem for graph transformation in [4]. The resulting graph modifications $G \xRightarrow{D_1} H_1 \xRightarrow{D_3} H$, $G \xRightarrow{D_2} H_2 \xRightarrow{D_4} H$ are sequentially independent. Vice versa, given sequentially independent $G \xRightarrow{D_1} H_1 \xRightarrow{D_3} H$, we can also construct the sequentially independent $G \xRightarrow{D_2} H_2 \xRightarrow{D_4} H$, s.t. $G \xRightarrow{D_1} H_1$ and $G \xRightarrow{D_2} H_2$ become parallel independent.

Example 3. Figure 4 shows two parallel independent graph modifications where $m_1 = (G \leftarrow D_1 \rightarrow H_1)$ is the refactoring modification from Figure 2, and $m_2 = (G \leftarrow D_2 \rightarrow H_2)$ deletes the transition from S2 to S4 and adds a new state named S5. We have four pushouts, thus both graph modifications may be performed in any order, yielding in both cases the same result H .

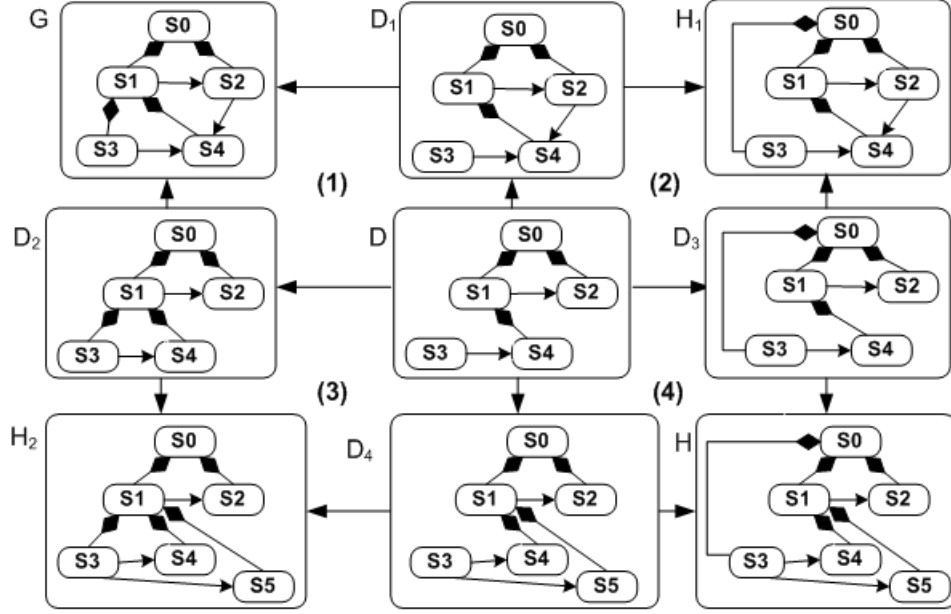


Fig. 4. Parallel independent graph modifications

3 Merging of Conflict-Free Graph Modifications

In the case that two graph modifications are parallel independent, they are called *conflict-free* and can be merged to one *merged graph modification* that realizes both original graph modifications simultaneously⁷ (see Definition 7).

In Theorem 2, we show that in case of parallel independence of $G \xRightarrow{D_i} H_i$ ($i = 1, 2$), the merged graph modification $G \xRightarrow{D} H$ is behaviourally equivalent to the parallel composition $G + G \xRightarrow{D_1 + D_2} H_1 + H_2$ of the original graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$). For the proof of Theorem 2 we need the concept of minimal rules which was introduced in [2] by Bisztray et al., where rules in the DPO approach to graph transformation [4] are also given by injective spans ($L \leftarrow K \rightarrow R$), but the intention is to apply them to graphs G via matches $o : L \rightarrow G$. A minimal rule can be constructed from a given graph modification and describes its changes in minimal context. The minimal rule generates the graph modification in the sense that we get a double pushout diagram according to the DPO approach to graph

⁷ Note that the merge construction in Definition 7 corresponds to the construction in [11].

transformation [4] with the minimal rule on top and the graph modification resulting from the rule application.

Definition 6 (Minimal graph rule and transformation). Rule $p = (L \xleftarrow{l} K \xrightarrow{r} R)$ is minimal over graph modification $G \xleftarrow{g} D \xrightarrow{h} H$ if the outer DPO exists and for each rule $L' \xleftarrow{l'} K' \xrightarrow{r'} R'$ with injective morphism $K' \rightarrow D$ and pushouts (3) (4), there are unique morphisms $L \rightarrow L'$, $K \rightarrow K'$, and $R \rightarrow R'$ such that the following diagram commutes and (1), (2), (1) + (3), and (2) + (4) are pushouts. Graph transformation $G \xRightarrow{p} H$ is also called minimal.

$$\begin{array}{ccccc}
 L & \xleftarrow{l} & K & \xrightarrow{r} & R \\
 \downarrow & (1) & \downarrow & (2) & \downarrow \\
 L' & \xleftarrow{l'} & K' & \xrightarrow{r'} & R' \\
 \downarrow & (3) & \downarrow & (4) & \downarrow \\
 G & \xleftarrow{g} & D & \xrightarrow{h} & H
 \end{array}$$

Theorem 1 (Characterization of Parallel Independent Graph Modifications). Given graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$) with minimal rules p_i and minimal transformations $G \xRightarrow{p_i} H_i$ ($i = 1, 2$), then the following statements are equivalent:

1. $G \xRightarrow{D_i} H_i$ ($i = 1, 2$) are parallel independent graph modifications,
2. $G \xRightarrow{p_i} H_i$ ($i = 1, 2$) are parallel independent DPO transformations.

Proof Idea (For the full proof, see Section A.1).

The equivalence of statements 1 and 2 can be shown using the minimality of minimal rules according to Definition 6, pushout decomposition as well as the construction of parallel independence in the DPO-approach [4]. \square

Now we define the merging construction of two conflict-free graph modifications and show that the result is behaviourally equivalent to their parallel composition.

Definition 7 (Merging Conflict-Free Graph Modifications). Given parallel independent graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$). Then, graph modification $G \xRightarrow{D} H$ given by $G \leftarrow D \rightarrow H$ defined by the diagonals of pushouts (1), (4) in Definition 4 is called merged graph modification of $G \xRightarrow{D_i} H_i$ ($i = 1, 2$).

Theorem 2 (Behavioural Equivalence of Merged Graph Modification). Given parallel independent graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$), and their merged graph modification $G \xRightarrow{D} H$ in the sense of Definition 7. Then, $G \xRightarrow{D} H$ is behaviourally equivalent to the parallel composition $G + G \xRightarrow{D_1 + D_2} H_1 + H_2$ of the original graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$).

Proof Idea (For the full proof, see Section A.2).

Using the minimal transformations with minimal rules $p_i = (L_i \leftarrow K_i \rightarrow R_i)$ for the graph modifications $G \xRightarrow{D_i} H_i = (G \leftarrow D_i \rightarrow H_i)$ ($i = 1, 2$), we show that two graph modifications are parallel independent iff their minimal transformations are parallel independent. Using the characterization of parallel independence for graph modifications in Theorem 1 and the parallelism theorem for DPO-transformations in [4], we obtain the four pushouts in the diagram to the right, showing the required behavioural equivalence. \square

$$\begin{array}{ccccc}
 G + G & \xleftarrow{\quad} & D_1 + D_2 & \xrightarrow{\quad} & H_1 + H_2 \\
 \uparrow & & \uparrow & & \uparrow \\
 L_1 + L_2 & \xleftarrow{\quad} & K_1 + K_2 & \xrightarrow{\quad} & R_1 + R_2 \\
 \downarrow & & \downarrow & & \downarrow \\
 G & \xleftarrow{\quad} & D & \xrightarrow{\quad} & H
 \end{array}
 \begin{array}{ccc}
 (PO) & & (PO) \\
 (PO) & & (PO)
 \end{array}$$

Remark 5. Theorem 2 motivates why in case of parallel independence of $G \xRightarrow{D_i} H_i$ ($i = 1, 2$) the merged graph modification $G \xRightarrow{D} H$ realizes both graph modifications simultaneously. This is expressed by behavioural equivalence to the parallel composition. Moreover, it is equal to the sequential compositions of $G \xRightarrow{D_1} H_1 \xRightarrow{D_3} H$ and $G \xRightarrow{D_2} H_2 \xRightarrow{D_4} H$ in Definition 4.

Example 4. The merged graph modification of the two parallel independent graph modifications $m_1 = (G \leftarrow D_1 \rightarrow H_1)$ and $m_2 = (G \leftarrow D_2 \rightarrow H_2)$ in Figure 4 is given by $m = (G \leftarrow D \rightarrow H)$. Obviously, m realizes both graph modifications m_1 and m_2 simultaneously. Due to Theorem 2, m is behaviourally equivalent to the parallel composition of m_1 and m_2 , $G + G \xRightarrow{D_1 + D_2} H_1 + H_2$, and equal to the sequential compositions $G \xRightarrow{D_1} H_1 \xRightarrow{D_3} H$ and $G \xRightarrow{D_2} H_2 \xRightarrow{D_4} H$.

4 Conflict Resolution

If two graph modifications have conflicts, a merge construction according to Definition 7 is not possible any more. In this section, we propose a general merge construction that resolves conflicts by giving *insertion* priority over *deletion* in case of delete-insert conflicts. The result is a merged graph modification where the changes of both original graph modifications are realized as far as possible. We state the properties of the general merge construction and show that the merge construction for the conflict-free case is a special case of the general merge construction.

Definition 8 (Conflicts of Graph Modifications).

1. Two modifications $m_i = G \xRightarrow{D_i} H_i$ ($i = 1, 2$) are conflict-free if they are parallel independent (i.e. we have four pushouts according to Definition 4).
2. They are in conflict if they are not parallel independent.
3. They are in delete-delete conflict if $\exists x \in (G \setminus D_1) \cap (G \setminus D_2)$.
4. (m_1, m_2) are in delete-insert conflict if

$$\exists \text{ edge } e \in H_2 \setminus D_2 \text{ with } s(e) \in D_2 \cap (G \setminus D_1) \text{ or } t(e) \in D_2 \cap (G \setminus D_1).$$

Remark 6. Note that for $m_i = (G \xRightarrow{D_i} H_i)$ ($i = 1, 2$) conflict-freeness, conflicts and delete-delete conflicts are symmetric, but (m_1, m_2) in delete-insert conflict (i.e. deletion of a node n in m_1 and insertion of an edge attaching the edge to node n in m_2 is different from (m_2, m_1) in delete-insert conflict (i.e. deletion in m_2 and insertion in m_1).

Example 5. Consider the graph modifications $m_1 = G \leftarrow D_1 \rightarrow H_1$ and $m_2 = G \leftarrow D_2 \rightarrow H_2$ in Figure 2. (m_2, m_1) are in *delete-insert* conflict because m_2 deletes node S3 which is needed by m_1 for the insertion of an edge. Moreover, m_1 and m_2 are in *delete-delete* conflict because the edge from S1 to S3 is deleted by both m_1 and m_2 . (m_1, m_2) are not in delete-insert conflict.

If two modifications m_1 and m_2 are in conflict, then at least one conflict occurs which can be of the following kinds:

1. both modifications delete the same graph element,
2. m_1 deletes a node which shall be source or target of a new edge inserted by m_2 ,
3. m_2 deletes a node which shall be source or target of a new edge inserted by m_3 .

Of course, several conflicts may occur simultaneously. In fact, all three conflict situations may occur independently of each other. For example, (m_1, m_2) may be in delete-delete conflict, but not in delete-insert conflict, or vice versa.⁸

Theorem 3 characterizes the kinds of conflicts that parallel dependent graph modifications may have.

⁸ In the worst case, we may have all kinds of conflicts simultaneously.

Theorem 3 (Characterization of Conflicts of Graph Modifications). *Given $m_i = (G \xrightarrow{D_i} H_i)$ ($i = 1, 2$), then (m_1, m_2) are in conflict iff*

1. (m_1, m_2) are in delete-delete conflict, or
2. (m_1, m_2) are in delete-insert conflict, or
3. (m_2, m_1) are in delete-insert conflict.

Proof Idea (For the full proof, see Section A.3). Parallel independence of (m_1, m_2) is equivalent to the fact that (PB_1) is also pushout, and the pushout complements (POC_1) and (POC_2) exist, such that pushout (PO_3) can be constructed. By negation, statements 1. - 3. are equivalent to 4. - 6., respectively:

$$\begin{array}{ccccc}
 G & \longleftarrow & D_1 & \longrightarrow & H_1 \\
 \uparrow & (PB_1) & \uparrow & (POC_1) & \uparrow \\
 D_2 & \longleftarrow & D & \longrightarrow & D_3 \\
 \downarrow & (POC_2) & \downarrow & (PO_3) & \downarrow \\
 H_2 & \longleftarrow & D_4 & \longrightarrow & H
 \end{array}$$

4. (PB_1) is not a pushout, i.e. $D_1 \rightarrow G \leftarrow D_2$ is not jointly surjective.
5. The dangling condition for $D \rightarrow D_2 \rightarrow H_2$ is not satisfied.
6. The dangling condition for $D \rightarrow D_1 \rightarrow H_1$ is not satisfied.

The *dangling condition* mentioned in statements 5. - 6. is the one known from DPO graph transformation [4]. It is satisfied by inclusions $D \rightarrow D_i \rightarrow H_i$ ($i = 1, 2$), if $\forall e \in H_i \setminus D_i : (s(e) \in D_i \implies s(e) \in D) \wedge (t(e) \in D_i \implies t(e) \in D)$. $s(e)$ and $t(e)$ are called *dangling points*. If the dangling condition is satisfied by $D \rightarrow D_i \rightarrow H_i$, the pushout complement (POC_i) can be constructed. \square

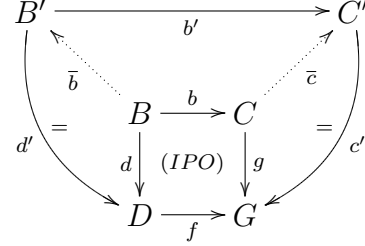
For delete-insert conflicts, our preferred resolution strategy is to preserve the nodes in the merged graph modification that are needed to realize the insertion of edges. If deletion is preferred instead, it has to be done manually after the automatic construction of the merged graph modification, supported by visual conflict indication. Ideally, deletion is done such that predefined meta-model constraints are fulfilled afterwards (see conclusion).

In the following, we define a general merge construction yielding the desired merged graph modification for two given graph modifications with conflicts. In the special case that we have parallel independent graph modifications, it coincides with the conflict-free merge construction in Definition 7.

For the general merge construction, we need so-called *initial pushouts*. In a nutshell, an initial pushout over a graph morphism $f : D \rightarrow G$ extracts a minimal graph morphism $b : B \rightarrow C$ where the context C contains all non-mapped parts of G , and the boundary B consists of those nodes in D that are used for edge insertion [4].

Definition 9 (Initial pushout). Let $f: D \rightarrow G$ be a graph morphism, an initial pushout over f consists of graph morphisms $g: C \rightarrow G$, $b: B \rightarrow C$, and injective $d: B \rightarrow D$ such that f and g are a pushout over b and d .

For every other pushout over f consisting of $c': C' \rightarrow G$, $b': B' \rightarrow C'$, and injective $d': B' \rightarrow D$, there are unique graph morphisms $\bar{b}: B \rightarrow B'$ and $\bar{c}: C \rightarrow C'$ such that $c' \circ \bar{c} = g$ and $d' \circ \bar{b} = d$. Moreover, it is required that (\bar{c}, b') is a pushout over (b, \bar{b}) .



Note that for graph morphisms, there is a canonical construction for initial pushouts [4].

Example 6 (Initial pushout). In Figure 5, the initial pushout IPO_1 over the morphism $D_1 \rightarrow H_1$ of graph modification m_1 in Figure 2 is shown. The morphism $B_1 \rightarrow C_1$ contains in a minimal context the insertion of the containment edge from S0 to S3.

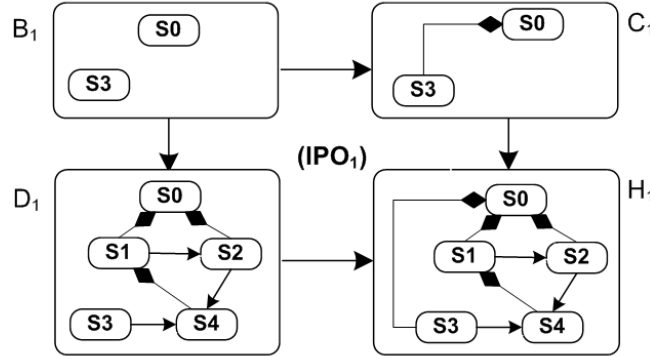


Fig. 5. Initial pushout over morphism $D_1 \rightarrow H_1$

Now, we are ready to present our general merge construction for graph modifications (see Definition 10). Analogously, to the merging of conflict-free graph modifications we start with constructing the intersection D of the intermediate graphs D_1 and D_2 . In case of delete-insert conflicts where a node is supposed to be deleted by one modification and used as source or target by the other modification, D is

too small, i.e. does not contain such nodes. Therefore, we look for a construction which enlarges D to the intermediate graph for the merged modification where insertion is prior to deletion: At first, we identify all these insertions in modifications 1 and 2. This is done by initial pushout construction (as described above) leading to $B_i \rightarrow C_i (i = 1, 2)$. By constructing first the intersection D_i^* of B_i and D in D_i and thereafter the union \overline{D}_i of B_i and D via D_i^* , graph D is extended by exactly those graph elements in B_i needed for insertion later on resulting in \overline{D}_i . After having constructed these extended intermediate graphs \overline{D}_1 and \overline{D}_2 , they have to be glued to result in the intermediate graph \overline{D} of the merged graph modification. Thereafter, the insertions identified by $B_i \rightarrow C_i (i = 1, 2)$ can be transferred to $\overline{D}_i \rightarrow X_i (i = 1, 2)$ first and to $\overline{D} \rightarrow \overline{X}_i (i = 1, 2)$ thereafter. Finally, they are combined by gluing \overline{X}_1 and \overline{X}_2 via \overline{D} yielding result graph H . Since \overline{D} is D extended by graph elements which are not to be deleted, (they are needed for insertion or come from G originally) \overline{D} can be embedded into G and thus, can function as intermediate graph for the merged graph modification $G \leftarrow \overline{D} \rightarrow H$.

Definition 10 (Merged Graph Modification in General). *Given two graph modifications $G \leftarrow D_1 \rightarrow H_1$ and $G \leftarrow D_2 \rightarrow H_2$. We construct their merged graph modification $G \leftarrow \overline{D} \rightarrow H$ in 6 steps, leading to the following general merge construction diagram:*

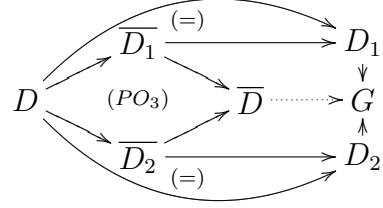
$$\begin{array}{ccccccc}
G & \longleftarrow & D_1 & \xrightarrow{id} & D_1 & \longrightarrow & H_1 \\
\uparrow & & \uparrow & (1) & \uparrow & & \uparrow \\
& & (PB_1) & & (PO_1) & & \\
D_2 & \longleftarrow & D & \longrightarrow & \overline{D}_1 & \longrightarrow & X_1 \\
\downarrow & & \downarrow & (2) & \downarrow & & \downarrow \\
id & & (PO_3) & & (PO_4) & & \\
D_2 & \longleftarrow & \overline{D}_2 & \longrightarrow & \overline{D} & \longrightarrow & \overline{X}_1 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
& & (PO_2) & & (PO_5) & & (PO_6) \\
H_2 & \longleftarrow & X_2 & \longrightarrow & \overline{X}_2 & \longrightarrow & H
\end{array}$$

1. Construct D by pullback (PB_1) of $D_1 \rightarrow G \leftarrow D_2$.
2. Construct initial pushouts (IPO_i) over $D_i \rightarrow H_i$ for $i = 1, 2$:

$$\begin{array}{ccccc}
B_i & \xrightarrow{\quad} & D_i & \xleftarrow{(3)} & \overline{D}_i \\
\downarrow & & \downarrow & & \downarrow \\
& & (IPO_i) & & (PO_i) \\
C_i & \xrightarrow{\quad} & H_i & \xleftarrow{\quad} & X_i
\end{array}$$

$$\begin{array}{ccccc}
& & D_i^* & & \\
& \swarrow & (PO) & \searrow & \\
B_i & \xrightarrow{\quad} & \overline{D}_i & \xleftarrow{\quad} & D \\
& \swarrow & (3) & \searrow & \\
& & D_i & &
\end{array}$$

3. Construct D_i^* as a pullback of $B_i \rightarrow D_i \leftarrow D$ and \overline{D}_i as pushout of $B_i \leftarrow D_i^* \rightarrow D$ with induced morphism $\overline{D}_i \rightarrow D_i$ with $B_i \rightarrow \overline{D}_i \rightarrow D_i = B_i \rightarrow D_i$ (3) and $D \rightarrow \overline{D}_i \rightarrow D_i = D \rightarrow D_i$ (4) for $(i = 1, 2)$.
4. Construct pushout $\overline{D}_i \rightarrow X_i \leftarrow C_i$ of $\overline{D}_i \leftarrow B_i \rightarrow C_i$ ($i = 1, 2$), leading by (3) to induced morphism $X_i \rightarrow H_i$ and pushout (PO_i) ($i = 1, 2$) by pushout decomposition. Moreover, (4) implies commutativity of (1) and (2) for $(i = 1, 2)$.
5. Now we are able to construct pushouts (PO_3) , (PO_4) , (PO_5) and (PO_6) one after the other.
6. Finally, we obtain the merged graph modification $(G \leftarrow \overline{D} \rightarrow H)$, where $\overline{D} \rightarrow H$ is defined by composition in (PO_6) , and $\overline{D} \rightarrow G$ is uniquely defined as induced morphism using pushout (PO_3) .



Remark 7. If the modifications $m_i = (G \leftarrow D_i \rightarrow H_i)$ ($i = 1, 2$) are parallel independent, then the pullback (PB_1) is a pushout and $\overline{D}_1 = D = \overline{D}_2 = \overline{D}$. In this case, the general merged modification $m = (G \leftarrow \overline{D} \rightarrow H)$ is equal up to isomorphism to the merged graph modification in the conflict-free case in Definition 7. If $m_i = (G \leftarrow D_i \rightarrow H_i)$ ($i = 1, 2$) are in delete-delete conflict, then the merged graph modification deletes the items that are deleted by both m_1 and m_2 since these items are not in D and hence not in \overline{D} .

Example 7. We construct the merged graph modification for graph modifications $m_1 = G \leftarrow D_1 \rightarrow H_1$ and $m_2 = G \leftarrow D_2 \rightarrow H_2$ in Figure 2. The construction diagram is shown in Figure 6.

According to step 3 in Definition 10, \overline{D}_1 has to be constructed as pushout of $B_1 \leftarrow D_1^* \rightarrow D$. D_1^* is the pullback of $B_1 \rightarrow D_1 \leftarrow D$, hence D_1^* consists just of the single node **S0**. Since B_1 contains two single nodes, **S0** and **S3**, we get as result of step 3 graph \overline{D}_1 which is similar to D but contains additionally node **S3**. Since (m_1, m_2) are not in delete-insert conflict, $\overline{D}_2 = D$. All remaining squares are constructed as pushouts.

Note that the resulting merged graph modification $G \leftarrow \overline{D} \rightarrow H$ preserves node **S3** because this node is deleted in m_2 although it is used for inserting a new edge in m_1 (resolution of the delete-insert conflict). The edge from **S1** to **S3** is deleted by the merged graph modification as it is deleted by both m_1 and m_2 (resolution of the delete-delete conflict). All graph objects created by either m_1 or m_2 are created also by the merged graph modification. Note that square (2) is a pushout in this example since (m_1, m_2) are not in delete-insert conflict.

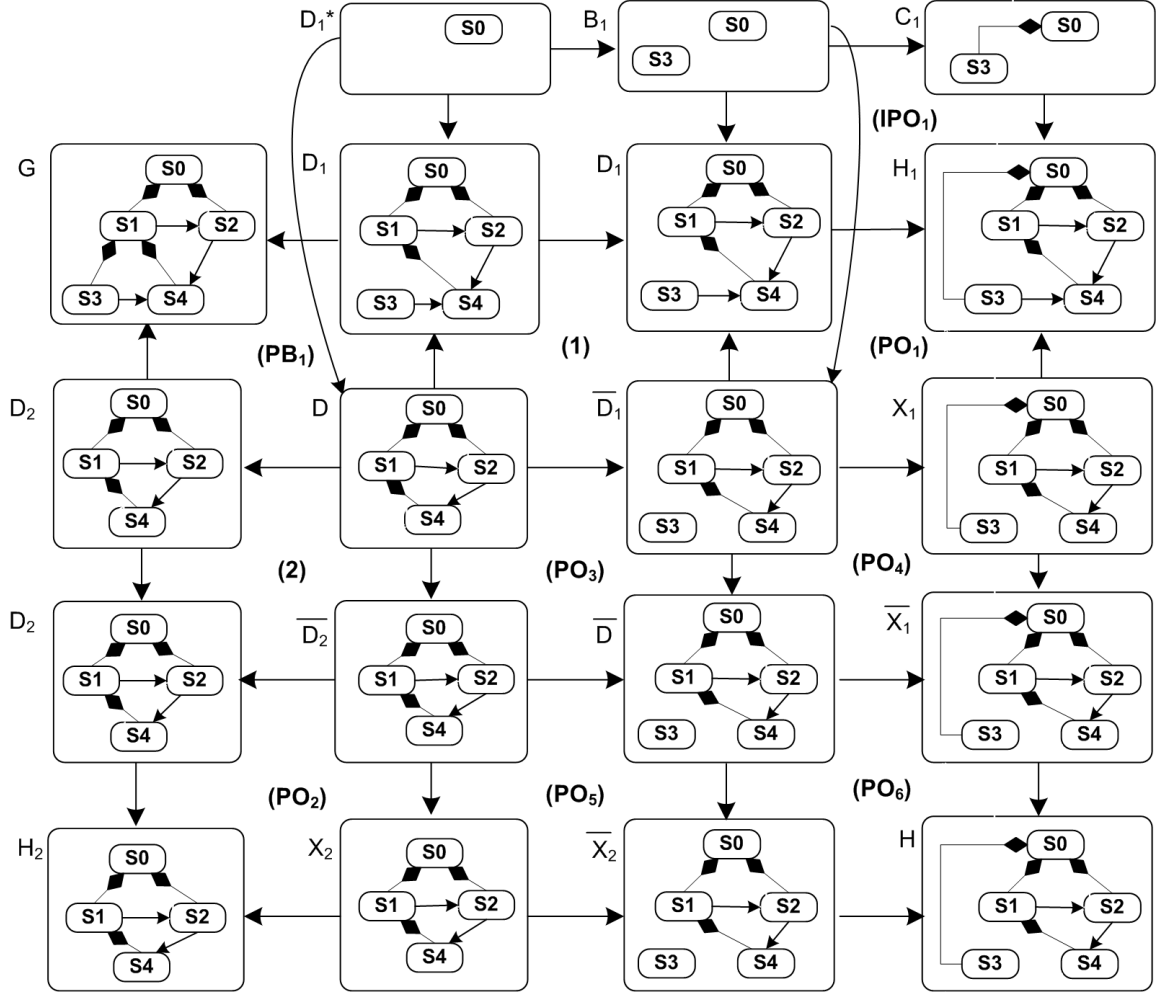


Fig. 6. General merge construction for conflicting graph modifications m_1 and m_2

The following theorem states that the modification resulting from the general merge construction specifies the intended semantics resolving delete-insert conflicts by preferring insertion over deletion:

Theorem 4 (Behaviour Compatibility of the General Merge Construction). *Given graph modifications $m_i = G \xRightarrow{D_i} H_i$ ($i = 1, 2$) with merged graph modification $m = G \xRightarrow{\bar{D}} H = (G \leftarrow \bar{D} \rightarrow H)$ in the sense of Definition 10. We use the following terminology for m (and similarly for m_1, m_2):*

$$\begin{aligned}
x \in G \text{ preserved by } m &\iff x \in \overline{D}, \\
x \in G \text{ deleted by } m &\iff x \in G \setminus \overline{D}, \\
x \in H \text{ created by } m &\iff x \in H \setminus \overline{D}.
\end{aligned}$$

Then, m is behaviour compatible with m_1 and m_2 in the following sense:

1. Preservation: $x \in G$ preserved by m_1 and $m_2 \implies x \in G$ preserved by m
 $\implies x \in G$ preserved by m_1 or m_2
2. Deletion: $x \in G$ deleted by m_1 and $m_2 \implies x \in G$ deleted by m
 $\implies x \in G$ deleted by m_1 or m_2
3. Preservation and Deletion: $x \in G$ preserved by m_1 and $x \in G$ deleted by m_2
 $\implies x \in G$ preserved by m , if $x \in \overline{D_1}$ ⁹
 $x \in G$ deleted by m , if $x \notin \overline{D_1}$ ¹⁰
(similar for $m_1, m_2, \overline{D_1}$ replaced by $m_2, m_1, \overline{D_2}$)
4. Creation: $x \in H_1$ created by m_1 or $x \in H_2$ created by m_2
 $\iff x \in H$ created by m

Proof Idea (For the full proof, see Section A.4. The preservation, deletion and creation results follow from the pushout properties of \overline{D} , the pushout complement properties of $\overline{D_1}, \overline{D_2}$ and the fact that $\overline{D_1}$ is pullback in the diagrams (PO_1) and (PO_4) (and analogously for $\overline{D_2}$). \square

Theorem 5 characterizes the three forms of conflict resolution which may occur.

Theorem 5 (Conflict Resolution by General Merge Construction). *Given graph modifications $m_i = G \xrightarrow{D_i} H_i$ ($i = 1, 2$) that are in conflict. The merge construction $m = (G \leftarrow \overline{D} \rightarrow H)$ resolves the conflicts in the following way:*

1. If (m_1, m_2) are in delete-delete conflict, with both m_1 and m_2 deleting $x \in G$, then x is deleted by m .
2. If (m_1, m_2) are in delete-insert conflict, there is an edge e_2 created by m_2 with $x = s(e_2)$ or $x = t(e_2)$ preserved by m_2 , but deleted by m_1 . Then x is preserved by m .
3. If (m_2, m_1) are in delete-insert conflict, there is an edge e_1 created by m_1 with $x = s(e_1)$ or $x = t(e_1)$ preserved by m_1 , but deleted by m_2 . Then x is preserved by m .

⁹ In this case, x is a node needed as source or target for an edge inserted by m_1 .

¹⁰ In this case, x is not needed for edge insertion by m_1 .

Proof Idea (For the full proof, see Section A.5). The resolution of delete-delete conflicts follows from the deletion property, and the resolution of delete-insert conflicts follows from the preservation-deletion property of the general merge construction in Theorem 4. \square

5 Related Work

First of all, we have to clarify that model merging differs from merging of model modifications. Model merging as presented e.g. in [8,10] is concerned with a set of models and their inter-relations expressed by binary relations. In contrast, merging of model modifications takes change operations into account. Merging of model modifications usually means that non-conflicting parts are merged automatically, while conflicts have to be resolved manually. In the literature, different resolution strategies which allow at least semi-automatic resolution are proposed. A survey on model versioning approaches and especially on conflict resolution strategies is given in [1]. Here, we focus on conflict resolution strategies.

A category-theoretical approach formalizing model versioning is given in [9]. Similar to our approach, modifications are considered as spans of morphisms to describe a partial mapping of models. Merging of model changes is defined by pushout constructions. However, conflict resolution is not yet covered by this approach in a formal way. A category theory-based approach for model versioning in-the-large is given in [3]. However, this approach is not concerned with formalizing conflict resolution strategies. A set-theoretic definition of EMF model merging is presented in [13], but conflicts are solved by the user and not automatically.

In [6] the applied operations are identified first and grouped into parallel independent subsequences then. Conflicts can be resolved by either (1) discarding complete subsequences, (2) combining conflicting operations in an appropriate way, or (3) modifying one or both operations. The choice of conflict resolution is made by the modeler. These conflict resolution strategies have not been formalized. The intended semantics is not directly investigated but the focus is laid on the advantage of identifying compound change operations instead of elementary ones. In contrast, we propose a semi-automatic procedure where at first, an automatic merge construction step gives insertion priority over deletion in case of delete-insert conflicts. If other choices are preferred, the user may perform deletions manually in a succeeding step.

Automatic merge results may not always solve conflicts adequately, especially state-based conflicts or inconsistencies may still exist or arise by the merge construction. Resolution strategies such as resolution rules presented in [7] are intended to solve state-based conflicts or inconsistencies. They can be applied in follow-up graph

transformations after the general conflict resolution procedure produced a tentative merge result. Moreover, Mens et al. discuss the problem that conflict resolution may give rise to new conflicts or inconsistencies and consider potential dependencies between model inconsistencies detection and resolution as well.

6 Conclusions and Future Work

In this paper, we have formalized a conflict resolution strategy for operation-based conflicts based on graph modifications. Our main result is a general merge construction for conflicting graph modifications. The merge construction realizes a resolution strategy giving insertion priority over deletion in case of delete-insert conflicts to get a merged graph modification result containing as much information as possible. We establish a precise relationship between the behaviour of the given graph modifications and the merged modification concerning deletion, preservation and creation of graph items. In particular, our general merge construction coincides with the conflict-free merge construction if the graph modifications are parallel independent. We show how different kinds of conflicts of given graph modifications are resolved by our automatic resolution strategy. It is up to an additional manual graph modification step to perform deletions that are preferred over insertions.

In [11], we presented two kinds of conflicts which can be detected based on graph modification: *operation-based* and *state-based* conflicts. Hence, in future work, our strategy for solving operation-based conflicts shall be extended by resolving also state-based conflicts. Here, repair actions should be provided to be applied manually by the modeler. Their applications would lead to additional graph modifications optimizing the merged graph modification obtained so far. For the specification of repair actions in this setting, the work by Mens et al. in [7] could be taken into account.

With regard to tool support, our graph transformation environment AGG [12] supports conflict analysis for graph rules and graph modifications. We plan to implement also the check of behavioural equivalence and the general merge construction for graph modifications in near future. This proof-of-concept implementation could function as blueprint for implementing our new resolution strategy in emerging model versioning tools.

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A Proofs

A.1 Proof of Theorem 1

Theorem 1 (Characterization of Parallel Independent Graph Modifications). *Given graph modifications $G \leftarrow D_i \rightarrow H_i$ ($i = 1, 2$) with minimal rules p_i and minimal transformations $G \xRightarrow{p_i} H_i$ ($i = 1, 2$), then the following statements are equivalent:*

1. $G \leftarrow D_i \rightarrow H_i$ are parallel independent graph modifications,
2. $G \xRightarrow{p_i} H_i$ are parallel independent DPO transformations.

Proof.

1. \implies 2.

From 1. we obtain pushouts (1) – (4). Let minimal transformations be given by pushouts (5), (6)) and (7), (8).

$$\begin{array}{ccccccc}
 & & L_1 & \longleftarrow & K_1 & \longrightarrow & R_1 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 L_2 & \longrightarrow & G & \xleftarrow{(5)} & D_1 & \longrightarrow & H_1 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 K_2 & \longrightarrow & D_2 & \xleftarrow{(1)} & D & \longrightarrow & D_3 \\
 & & \downarrow & & \downarrow & & \downarrow \\
 R_2 & \longrightarrow & H_2 & \xleftarrow{(3)} & D_4 & \longrightarrow & H
 \end{array}$$

(7) is indicated by a dotted arrow from L_2 to D_1 .
 (6) is indicated by a dotted arrow from R_1 to D_3 .
 (8) is indicated by a dotted arrow from R_2 to H .

By minimality in Lemma 1, we obtain especially unique morphisms $L_1 \rightarrow D_2$ and $L_2 \rightarrow D_1$ such that the corresponding triangles commute. This means that $G \xRightarrow{p_1} H_1$, $G \xRightarrow{p_2} H_2$ are parallel independent.

2. \implies 1.

Given parallel independent DPO-transformations by pushouts (5) – (8) and morphisms $L_1 \rightarrow D_2$ and $L_2 \rightarrow D_1$ such that the triangles commute. Then, D is constructed as pullback in (1) and can be shown to be also a pushout because $D_1 \rightarrow G \leftarrow D_2$ are jointly surjective. The pullback property of (1) and morphisms $K_1 \rightarrow D_1$, $K_1 \rightarrow L_1 \rightarrow D_2$ imply a unique $K_1 \rightarrow D$ such that the corresponding triangle commutes. In the next step, D_3 is constructed as pushout of $D \leftarrow K_1 \rightarrow R_1$, leading by pushout decomposition to pushout (2). Symmetrically, we obtain pushout (3) and finally (4) as pushout of $D_4 \leftarrow D \rightarrow D_3$. \square

Remark 8. In $(2. \implies 1.)$, it is sufficient to have any pair of rules p_1, p_2 generating DPO-transformations $G \xRightarrow{p_i} H_i$ ($i = 1, 2$); it is not necessary that p_1, p_2 are minimal.

A.2 Proof of Theorem 2

For the proof of Theorem 2, we need the construction of minimal rules by Bisztray et al. [2]. This construction yields in a natural way a minimal DPO rule for a graph modification. Minimal rules contain the proper atomic actions on graphs with minimal contexts. Bisztray et al. have shown that this construction is unique, i.e. no smaller rule than the minimal rule can be constructed for a given graph modification.

The following minimal rule construction extracts all deletion and creation actions from a given transformation in graphs L_1 and R_1 by constructing so-called *initial pushouts* (see Definition 9).

Definition 11 (Construction of Minimal Rules from Graph Modifications). Given a graph modification $G \leftarrow D \rightarrow H$, the minimal rule $L \leftarrow K \rightarrow R$ is constructed as follows:

1. Construct the initial pushouts (1) of $D \rightarrow G$ and (2) of $D \rightarrow H$

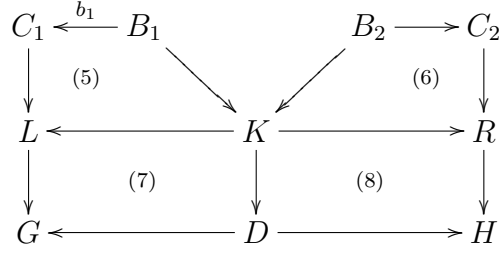
$$\begin{array}{ccccc}
 C_1 & \xleftarrow{b_1} & B_1 & & B_2 & \longrightarrow & C_2 \\
 \downarrow & (1) & \searrow & & \swarrow & (2) & \downarrow \\
 G & \xleftarrow{g} & D & \xrightarrow{h} & H
 \end{array}$$

2. Construct the pullback $B_1 \leftarrow P \rightarrow B_2$ of $B_1 \rightarrow D \leftarrow B_2$, and then the pushout $B_1 \rightarrow K \leftarrow B_2$ of $B_1 \leftarrow P \rightarrow B_2$, leading to unique injective morphism $K \rightarrow D$ such that (3), (4) commute.

$$\begin{array}{ccccc}
 & & P & & \\
 & \swarrow & & \searrow & \\
 C_1 & \xleftarrow{b_1} & B_1 & & B_2 & \longrightarrow & C_2 \\
 \downarrow & (1) & \searrow & & \swarrow & (2) & \downarrow \\
 G & \xleftarrow{g} & D & \xrightarrow{h} & H \\
 & & \uparrow & & \\
 & & K & &
 \end{array}$$

(3) (4)

3. Finally split initial pushouts (1) and (2) by (3) and (4), i.e. construct pushouts (5) of $C_1 \leftarrow B_1 \rightarrow K$ and (6) of $K \leftarrow B_2 \rightarrow C_2$, leading to pushouts (7) and (8) by pushout decomposition, and the minimal rule $L \leftarrow K \rightarrow R$.

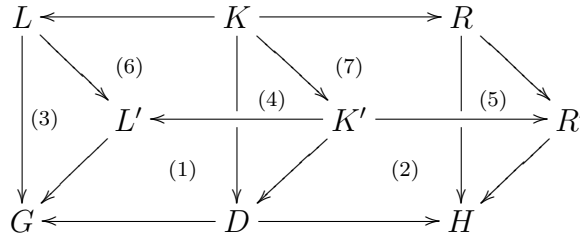


The DPO (7),(8) is called *minimal transformation* of $G \leftarrow D \rightarrow H$ via the minimal rule $L \leftarrow K \rightarrow R$.

Note that after Step 1, the minimal rule extraction may also be considered as E-concurrent rule constructed from a deletion rule on the left and a creation rule on the right.

The following lemma shows that the minimal rule construction in Definition 11 satisfies the axiomatic requirement of Definition 6.

Lemma 1 (Minimality of Minimal Rule and Transformation). *Given any rule $L' \leftarrow K' \rightarrow R'$ which generates $G \leftarrow D \rightarrow H$ with injective match via pushouts (1) and (2) below, and the outer diagram is a DPO with minimal rule and minimal transformation. Then, there are unique injective morphisms $L \rightarrow L'$, $K \rightarrow K'$ and $R \rightarrow R'$ such that (3) – (5) commute and (6), (7) are pushouts.*



Proof. The proof of Lemma 1 is given in [2]. □

Example 8 (Minimal rule construction). The construction of the minimal rule p_1 for graph modification m_1 in Figure 2 is depicted in Fig. 7.

Now we can show the behavioural equivalence of the parallel composition of two parallel independent graph modifications with their corresponding merged graph modification.

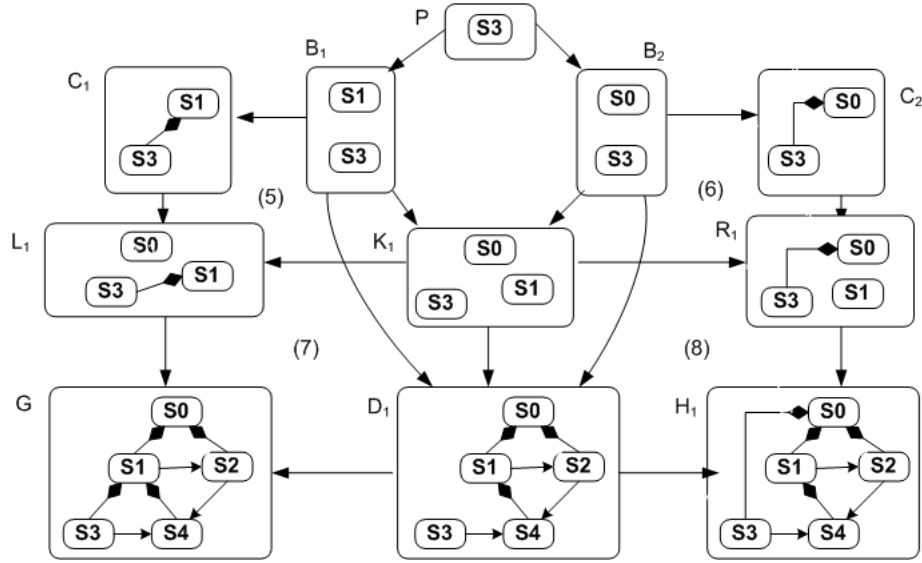


Fig. 7. Construction of minimal rule $p_1 = (L_1 \leftarrow K_1 \rightarrow R_1)$ for m_1

Theorem 2 (Behavioural Equivalence of Merged Graph Modification).

Given parallel independent graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$), and their merged graph modification $G \xRightarrow{D} H = G \leftarrow D \rightarrow H$ in the sense of Definition 7. Then, $G \leftarrow D \rightarrow H$ is behavioural equivalent to the parallel composition $G + G \xRightarrow{D_1 + D_2} H_1 + H_2$ of the original graph modifications $G \xRightarrow{D_i} H_i$ ($i = 1, 2$).

Proof. Let $p_1 = (L_1 \leftarrow K_1 \rightarrow R_1)$ and $p_2 = (L_2 \leftarrow K_2 \rightarrow R_2)$ be the minimal rules for $G \leftarrow D_1 \rightarrow H_1$ and $G \leftarrow D_2 \rightarrow H_2$, respectively, with DPO-transformations $G \xRightarrow{p_1} H_1$ and $G \xRightarrow{p_2} H_2$, which are parallel independent according to the Characterization Theorem 1 below. By the DPO Parallelism Theorem [4] we have $G \xRightarrow{p_1 + p_2} H$ with DPO

$$\begin{array}{ccccc}
 L_1 + L_2 & \longleftarrow & K_1 + K_2 & \longrightarrow & R_1 + R_2 \\
 \downarrow & (1) & \downarrow & (2) & \downarrow \\
 G & \longleftarrow & D & \longrightarrow & H
 \end{array}$$

where $G \leftarrow D \rightarrow H$ coincides with the span defined by parallel independence of $G \xRightarrow{D_i} H_i$. Since $G \xRightarrow{p_1} H_1, G \xRightarrow{p_2} H_2$ are transformations via the minimal rules, we get the pushouts (4) – (7) and hence also (8) = (4) + (6) and (9) = (4) + (7):

$$\begin{array}{ccccc}
L_1 \longleftarrow K_1 \longrightarrow R_1 & L_2 \longleftarrow K_2 \longrightarrow R_2 & L_1 + L_2 \longleftarrow K_1 + K_2 \longrightarrow R_1 + R_2 \\
\downarrow (4) \quad \downarrow (5) \quad \downarrow & \downarrow (6) \quad \downarrow (7) \quad \downarrow & \downarrow (8) \quad \downarrow (9) \quad \downarrow \\
G \longleftarrow D_1 \longrightarrow H_1 & G \longleftarrow D_2 \longrightarrow H_2 & G + G \longleftarrow D_1 + D_2 \longrightarrow H_1 + H_2
\end{array}$$

Pushouts (1), (2) and (8), (9) show that the merge $G \xRightarrow{D} H$ given by $G \leftarrow D \rightarrow H$ is behavioral equivalent to the parallel composition $G + G \xRightarrow{D_1 + D_2} H_1 + H_2$ given by $G + G \leftarrow D_1 + D_2 \rightarrow H_1 + H_2$. \square

A.3 Proof of Theorem 3

Theorem 3 (Characterization of Conflicts of Graph Modifications). *Given $m_i = (G \xRightarrow{D_i} H_i)$ ($i = 1, 2$), then (m_1, m_2) are in conflict iff*

1. (m_1, m_2) are in delete-delete conflict, or
2. (m_1, m_2) are in delete-insert conflict, or
3. (m_2, m_1) are in delete-insert conflict.

Proof. Parallel independence of (m_1, m_2) is equivalent to the fact that PB_1 is pushout, the pushout complement (POC_1) exists, and (POC_2) exists. In this case, we can construct (PO_3) as pushout.

$$\begin{array}{ccccc}
G \longleftarrow D_1 \longrightarrow H_1 & & & & \\
\uparrow (PB_1) & \uparrow (POC_1) & \uparrow & & \\
D_2 \longleftarrow D \longrightarrow D_3 & & & & \\
\downarrow (POC_2) & \downarrow (PO_3) & \downarrow & & \\
H_2 \longleftarrow D_4 \longrightarrow H & & & &
\end{array}$$

First of all, we have (m_1, m_2) not parallel independent is equivalent to

1. (PB_1) is no pushout, i.e. $D_1 \rightarrow G \leftarrow D_2$ is not jointly surjective, or
2. the pushout complement POC_2 does not exist, i.e. the gluing condition for $D \rightarrow D_2 \rightarrow H_2$ is not satisfied, or
3. the pushout complement POC_1 does not exist, i.e. the gluing condition for $D \rightarrow D_1 \rightarrow H_1$ is not satisfied.

In fact, if the negation of all conditions 1. – 3. were satisfied, we would have four pushouts and hence parallel independence. Now we have:

1. $\iff (m_1, m_2)$ are in delete-delete conflict,

2. $\iff \exists$ dangling point $x \in D_2$ which is not a gluing point, i.e. $x \notin D$
 $\iff \exists$ edge $e \in H_2 \setminus D_2$ with $s(e) \in D_2 \setminus D$ or $t(e) \in D_2 \setminus D$
 $\stackrel{(*)}{\iff} \exists$ edge $e \in H_2 \setminus D_2$ with $s(e) \in D_2 \cap (G \setminus D_1)$ or $t(e) \in D_2 \cap (G \setminus D_1)$
 $\iff (m_1, m_2)$ are in delete-insert conflict
 (where $\stackrel{(*)}{\iff}$ follows from $x \in D_2 \setminus D \iff x \in D_2 \cap (G \setminus D_1)$ as follows:
 $x \in D_2 \setminus D \iff x \in D_2 \setminus D_1 \iff x \in D_2 \cap (G \setminus D_1)$ using the pullback property of (PB_1) .)
3. $\iff (m_2, m_1)$ are in delete-insert conflict (analogously to 2.). \square

A.4 Proof of Theorem 4

Theorem 4 (Behaviour Compatibility of the General Merge Construction.) *Given graph modifications $m_i = G \xrightarrow{D_i} H_i$ ($i = 1, 2$) with merged graph modification $m = G \xrightarrow{D} H = (G \leftarrow \overline{D} \rightarrow H)$ in the sense of Definition 10. Then, m is behaviour compatible with m_1 and m_2 in the following sense:*

1. *Preservation*
 $(x \in G \text{ preserved by } m_1 \text{ and } m_2) \implies (x \in G \text{ preserved by } m)$
 $\implies (x \in G \text{ preserved by } m_1 \text{ or } m_2)$
2. *Deletion*
 $(x \in G \text{ deleted by } m_1 \text{ and } m_2) \implies (x \in G \text{ deleted by } m)$
 $\implies (x \in G \text{ deleted by } m_1 \text{ or } m_2)$
3. *Preservation and Deletion*
 $(x \in G \text{ preserved by } m_1 \text{ and } x \in G \text{ deleted by } m_2)$
 $\implies x \in G \text{ preserved by } m, \text{ if } x \in \overline{D}_1$
 $x \in G \text{ deleted by } m, \text{ if } x \notin \overline{D}_1$
 (similar for m_1, m_2, \overline{D}_1 replaced by m_2, m_1, \overline{D}_2)
4. *Creation*
 $(x \in H_1 \text{ created by } m_1 \text{ or } x \in H_2 \text{ created by } m_2) \iff (x \in H \text{ created by } m)$

Proof.

1. *Preservation:*
 (a) $x \in G$ preserved by m
 $\implies x \in \overline{D} \implies x \in H, \overline{D}$ pushout \implies w.l.o.g. $x \in \overline{D}_1$
 $\implies x \in D_1 \implies x \in H_1$
 $\implies x \in G$ preserved by m_1 or $x \in G$ preserved by m_2

(b) $x \in G$ preserved by m_1 and $x \in G$ preserved by m_2
 $\implies x \in D_1$ and $x \in D_2$
 $\implies x \in D_1 \cap D_2 = D \implies x \in \overline{D}$
 $\implies x$ preserved by m

2. Deletion:

(a) $x \in G$ deleted by m
 $\implies x \in G \setminus \overline{D}$

Assume $x \in G$ not deleted by m_1 and $x \in G$ not deleted by m_2
 $\implies x \in G \wedge x \in D_1 \wedge x \in D_2 \implies x \in D \implies x \in \overline{D}$ (contradiction)

$\implies x \in G$ deleted by m_1 or $x \in G$ deleted by m_2

(b) $x \in G$ deleted by m_1 and $x \in G$ deleted by m_2
 $\implies x \in G \setminus D_1$ and $x \in G \setminus D_2$

Assume $x \in G$ not deleted by m

$\implies x \in \overline{D} \xrightarrow{\overline{D}PO} x \in \overline{D_1}$ or $x \in \overline{D_2}$
if $x \in \overline{D_1} \implies x \in D_1$ (contradiction)
if $x \in \overline{D_2} \implies x \in D_2$ (contradiction)

$\implies x \in G$ deleted by m .

3. Preservation and Deletion:

$x \in G$ preserved by m_1 and $x \in G$ deleted by m_2

$\implies x \in G$ and $x \in D_1$ and $x \notin D_2$

Case 1: $x \in \overline{D_1} \implies x \in \overline{D} \implies x \in G$ preserved by m

Case 2: $x \notin \overline{D_1}$

Assume $x \in \overline{D}$

$\implies x \in \overline{D_1} \vee x \in \overline{D_2}$ (where both cases lead to a contradiction)

$\implies x \notin \overline{D} \implies x \in G$ deleted by m

\implies If $x \in \overline{D_1}$, then $x \in G$ is preserved by m .

If $x \notin \overline{D_1}$, then $x \in G$ is deleted by m .

4. Creation:

(a) $x \in H$ created by m

$\implies x \in H \setminus \overline{D} \implies x \in X_1$ or $x \in X_2$ (w.l.o.g. $x \in X_1$) $\implies x \in H_1$

Assume $x \in D_1 \implies x \in \overline{D_1}$ because (PO_1) (the upper right square of the diagram in Definition 10) is pullback

$\implies x \in \overline{D}$ (contradiction)

$\implies x \notin D_1 \implies x \in H_1 \setminus D_1$

$\implies x \in H_1$ created by m_1 or $x \in H_2$ created by m_2

(b) $x \in H_1$ created by m_1 or $x \in H_2$ created by m_2
 $\implies x \in H_1 \setminus D_1 \xRightarrow{(PO_1)} x \in X_1 \implies x \in H$
 Assume $x \in \overline{D} \xRightarrow{(PO_4)} x \in \overline{D_1}$ (where (PO_4) is also pullback)
 $\implies x \in D_1$ (contradiction)
 $\implies x \notin \overline{D} \implies x \in H \setminus \overline{D}$
 $\implies x \in H$ created by m . □

Remark 9. The general merged modification $(G \leftarrow \overline{D} \rightarrow H)$ is in general not behaviour equivalent to the parallel composition $(G + G \leftarrow D_1 + D_2 \rightarrow H_1 + H_2)$, but we have the following categorical relationship, where (1), (2) and (4) are pushouts, but (3) is only commutative using the constructions of Definition 10.

$$\begin{array}{ccccc}
 G + G & \longleftarrow & D_1 + D_2 & \longrightarrow & H_1 + H_2 \\
 \uparrow & & \uparrow & & \uparrow \\
 & (1) & & (2) & \\
 \overline{D} + \overline{D} & \longleftarrow & \overline{D_1} + \overline{D_2} & \longrightarrow & X_1 + X_2 \\
 \downarrow & & \downarrow & & \downarrow \\
 & (3) & & (4) & \\
 G & \longleftarrow & \overline{D} & \longrightarrow & H
 \end{array}$$

A.5 Proof of Theorem 5

Theorem 5 (Conflict Resolution by General Merge Construction.) *Given graph modifications $m_i = G \xRightarrow{D_i} H_i$ ($i = 1, 2$) that are in conflict. The merge construction $m = (G \leftarrow \overline{D} \rightarrow H)$ resolves the conflicts in the following way:*

1. If (m_1, m_2) are in delete-delete conflict, with both m_1 and m_2 deleting $x \in G$, then x is deleted by m .
2. If (m_1, m_2) are in delete-insert conflict, there is an edge e_2 created by m_2 with $x = s(e_2)$ or $x = t(e_2)$ preserved by m_2 , but deleted by m_1 . Then x is preserved by m .
3. If (m_2, m_1) are in delete-insert conflict, there is an edge e_1 created by m_1 with $x = s(e_1)$ or $x = t(e_1)$ preserved by m_1 , but deleted by m_2 . Then x is preserved by m .

Proof.

1. Let $x \in G$ be deleted by m_1 and m_2 which implies that x is deleted by m according to the deletion property of the general merge construction in Theorem 4.

2. Let $e_2 \in H_2 \setminus D_2$ with $x = s(e_2) \in D_2 \cap (G \setminus D_1)$ or $x = t(e_2) \in D_2 \cap (G \setminus D_1)$. Thus, x is a dangling point for $\overline{D_2} \rightarrow D_2 \rightarrow H_2$. Using pushout (PO_2) , we conclude by the dangling condition that x is also dangling point, i.e. $x \in \overline{D_2}$ in our case. According to the preservation-deletion property of the general merge construction in Theorem 4, we get that x is preserved by m .
3. Symmetric to 2. □